# MATERIALS TREATMENT

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## MODELING OF DIAMOND DRILLING OF HOLES IN BRITTLE NONMETALLIC SOLID MATERIALS

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A model of diamond drilling of holes in brittle solid nonmetallic materials is proposed, which is based on describing the microcutting process performed by a single grain and the energy processes occurring in drilling. Modeling of single-grain work is performed taking into account deformation of the binder. The modeling results are used in specialized software for calculating cutting conditions and developing other advanced technologies for producing diamond tools operating under the most stringent conditions.

In manufacturing parts from nonmetallic materials (glass, quartz, ceramics, ferrite, and glass ceramics), formation of openings with diameters ranging from 1.0 to 1000 mm and cutting out cores are critical and labor-consuming operations. At present, diamond drills are most widely used for these purposes. An operating diamond drill can be represented as a wheel that polishes an opening with its end surface. Therefore, in contrast to a normal metal-cutting drill, whose design includes deep grooves for removal of cuttings, a rational design for a diamond tool intended for drilling nonmetallic materials is a thin-walled ring.

Diamond drills have diverse applications in the household, electrical engineering, radioelectronics, opticomechanical and watch-making sectors of industry, in making spectacle lenses, in jewelry, sculpture, art restoration, building and finishing works, and in the mechanical and tool-making industries.

In the general case of applying a diamond drill [1], this tool achieves quality 9 – 12 of precision in making holes. In using adjustable drills, the precision of holes can be improved by adjusting the cutting elements, which allow a compensation for the wear of the diamond-bearing part. In drilling parts made of glass, glass ceramic, or ferrite under optimum cutting conditions, the roughness of the surface $R_a = 1.1 – 1.9$ μm. As the microhardness of the material grows, the surface roughness decreases. Under the same conditions the surface roughness of ceramics TsM-332 $R_a = 0.3 – 0.6$ μm.

The depth of disturbances in the surface layer usually does not exceed 20 μm. Provided the technological conditions are satisfied, the size of the chips on whole edges is limited to 0.05 – 0.15 mm.

Diamond drilling of holes is inevitable in the production of microchip bases, scales, photodisks, light diodes, spectacle lenses, mirrors, insulators, fitting accessories, instrumental stones, and many other things. Therefore, development of a mathematical model for the machining process, which would encompass the multitude of factors affecting the drilling process and allow for calculation of treatment conditions with an optimum cost-quality effect, is topical.

The technological process of diamond drilling is an extremely strained type of machine treatment, in which the entire cutting surface of the drill is in constant contact with material treated, whereas supply of lubricant-coolant and removal of slime are impeded. Until recently there were no integrated models that would make it possible to describe most fully the diamond-drilling process with the aim of determining the optimum conditions of treatment, developing new advanced instruments, and creating systems for adaptive control of the process.

Let us analyze the main parameters of diamond drilling and the factors influencing the technological process (Fig. 1).

To determine the structure and relationships between the parameters and the process factors, we will be considering the technological system of diamond drilling as a controlled oriented object.

In order to model the drilling process, a complex model was developed based on describing the process of microcutting performed by a single diamond grain and the energy processes occurring in drilling.

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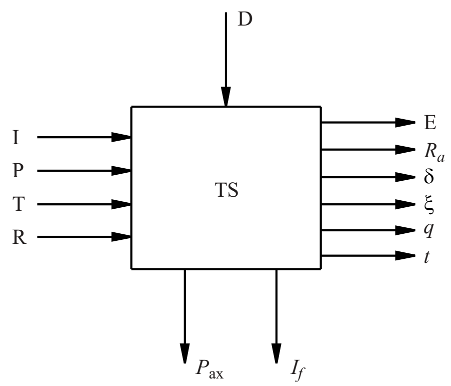


**Fig. 1.** Technological system of diamond drilling of brittle nonmetallic solid materials: TS) technological system of diamond drilling; *input parameters*: I) parameters of cutting instrument (drill); P) parameters of part treated; T) technological parameters of drilling process, R) treatment regimes; D) design parameters of holes treated; *output parameters*: $P_{ax}$) axial cutting force, kgf; $I_f$) modulation amplitude: acoustic emission parameter, V; E) drilling efficiency, mm$^3$/min; $R_a$) roughness of treated surface, μm; δ) thickness of defective (cracked) layer, mm; ξ) mean width of chips at the hole inlet, mm; $q$) specific consumption of diamond, mg/cm; $t$) temperature in the treatment zone, °C.

The route of motion of a single grain is described by the system of equations of the following form:

$$x = r \sin \varphi;$$

$$y = r \cos \varphi;$$

$$z = \frac{S}{n} \frac{\varphi}{360},$$

where $r$ is the distance from the drill center to the grain considered, mm; φ is the drill turning angle, deg; $S$ is the feed, mm/min; $n$ is the rotational speed of the drill, min$^{-1}$; $x$, $y$, and $z$ are the grain coordinates.

There are two approaches to modeling work of an individual grain: the grain is modeled as an absolutely rigid indenter [2] of a certain geometrical shape and hence treatment regimes are calculated, or else the binder is modeled separately, and processes of its deformation under the effect of the cutting force are studied. Both approaches have been integrated in the proposed model to obtain a system of equations giving a maximally reliable description of real drilling processes.

In experiments with microindenting, which is analogous to the performance of a single grain, Evans and Charles [3] obtained a relationship correlating the indenter imprint size to the hardness of the material and the crack length:

$$\frac{k_c \Phi}{H\sqrt{a}} = 0.48\left(\frac{C_L}{a}\right)^{-3/2},$$

where $k_c$ is the stress-intensity coefficient (crack-resistance parameter); $\Phi = H/\tau_{cr}$ is a constant (for brittle materials); $H$ is microhardness; $a$ is the half-diagonal of the indenter imprint; $C_L$ is the length of the lateral crack; $\tau_{cr}$ is the flow stress.

Upon contacting the material under treatment, the protruding surface of the grain starts incorporating into it [4]. A system of cutting forces influence the grain, striving to tear it out of the binder. Let us arbitrarily designate this part of the cutting process as phase 1.

The microhardness of the material being treated significantly exceeds the hardness of the binder; however it is lower than the microhardness of the diamond grain. The grain under these conditions starts deforming the more plastic binder and at the same time revolves around its axis under the effect of the cutting forces and penetrates into the material being treated.

It is established that the diamond indenter at the initial moment glides over the material of the part being treated and then elastic deformation is observed.

Since the process of destruction of brittle nonmetallic solids is brittle destruction, as soon as stresses in the material of the article reach a certain critical value, part of the material in front of the grain is chipped off. At the same time microcracks are formed, which facilitate further chipping and cause defects in the treated surface. Let us call this part of the process phase 2.

In diamond drilling, lateral cracks responsible for the size of the chips are the principal ones. An expression determining the length of the lateral crack can be written in the following form:

$$C_L = \left(\frac{P_{ax}^{ind}}{k_c}\right)^{3/4},$$

where $P_{ax}^{ind}$ is the axial force on the individual grain.

Immediately after chipping the cutting force drops to zero and the grain under the effect of elastic deformation of the binder returns to its initial position. Due to the residual deformation of the binding material, the setting site of the diamond grain increases (phase 3).

In some cases, when the bending strength of the binder exceeds the chipping strength of the material, phase 2 may be absent. In this case, brittle destruction follows immediately after phase 1.

The condition of transition from phase 2 to phase 3 taking into account the strength of the binder and the grain setting depth can be written as follows:

$$\sigma_b^b \le \frac{P_R^{II}}{F_g},$$

where $\sigma_b^b$ is the bending strength of the binder materials; $P_R^{II}$ is the resulting cutting force in phase 2; $F_g$ is the surface area of the grain existing in a binder (the surface area of a set grain).

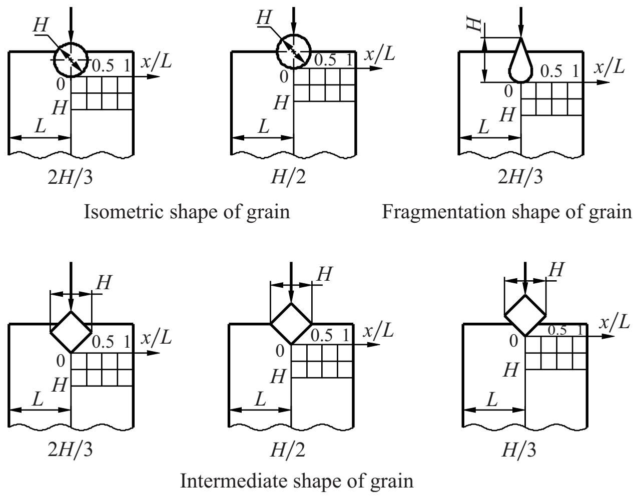


**Fig. 2.** Setting schemes of grains of different shapes.

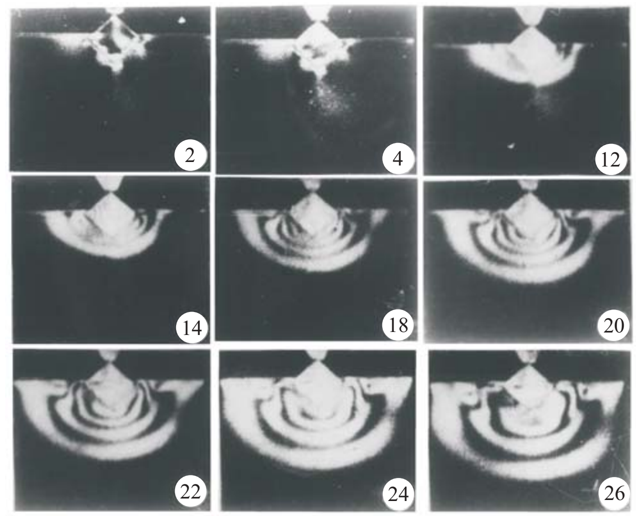


**Fig. 3.** Interference bands in grain – binder system (intermediate grain shape, setting depth $2H/3$). Numbers under each shot of videotape indicate time (in microseconds) that has passed since the moment of application of pulse load, i.e., since the emergence of the first symptoms of stress in the grain model.

An operating drill exists in a complex stressed state under the effect of the total dynamic load arising in its rotation and axial migration in contact with the material being treated.

The process of dynamic interaction of the grain – binder system with the material under treatment also involves a complex stressed state that depends on many factors: the geometrical shape of the grain, the depth of its setting in the binder and its adhesion to the binder; the presence (absence) of pores in the drill structure; interaction of the grain with the neighboring grains, etc.

Abrasive grains located at the periphery of the drill multiply enter into contact with the article being treated, the duration of such contact measured in tens of microseconds. Due to shock loads on individual abrasive grains, a binder is required to allow for "rocking" of the grains under the effect of these loads and, furthermore, could partly absorb impacts.

Therefore, it is essential to study stresses arising in the grain – binder system under dynamic loads [5]. The experiments performed investigated the effect of the shape and setting depth of abrasive grains and the direction of loads on the stressed state of grains.

The stressed state of the binder was investigated at different sections along its depth. Three sections of the binder were considered for grains of different shapes (Fig. 2): section 0) immediately adjacent to the grain; $H/2$) at a distance of half-height of the grain from the first section; and $H$) at a distance equal to the grain height from section zero (Fig. 2).

Figure 3 shows fragments of filming of interference bands under pulse loading of the grain – binder model. The shots show well enough the propagation of stress waves in the binder model, which makes it possible to construct a time dependence of maximum tangential stresses along the binder sections considered. With respect to values of maximum tangential stresses arising in the binder under pulse loading, the grains of an isometric or fragmentation shape are similar, whereas relatively lower stresses are observed for the grain of an intermediate shape (Fig. 4).

Figure 5 indicates variation of the maximum tangential stresses for grains of the intermediate shape selected as the main shape in mathematical modeling.

As a result of microcutting modeling, dependences were obtained that correlate axial force, the cutting velocity, feed, drill parameters, and wear of grains and the binder, which af-

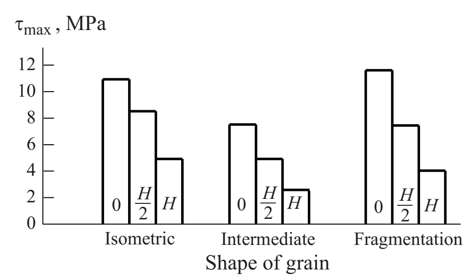


**Fig. 4.** Comparative diagram of maximum tangential stresses in binder for systems with various grain shapes (setting depth $2H/3$).

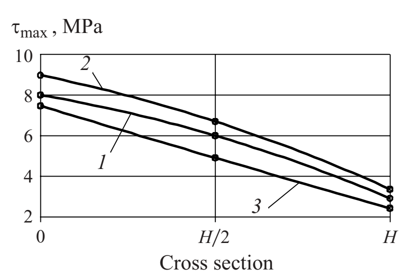


**Fig. 5.** Variations of maximum tangential stresses versus depth of binder for an intermediate-shape grain: *1*, *2*, and *3*) setting depth $H/2$, $H/3$, and $2H/3$, respectively.

fect self-sharpening of the tool. Some of these dependences are described by a system of equations:

$$V_{\rm ch}^{\rm r} = 23\left(\frac{P_{\rm ax}^{\rm ind}}{k_c n_m}\right)^{3/2} \pi R_{\rm dr} n_m^{\rm c};$$

$$n_m^{\rm c} = (n_m k_{\rm cg}^{\rm I} k_{\rm yo}^{\rm I}) + (n_m k_{\rm cg}^{\rm II} k_{\rm yo}^{\rm II});$$

$$n_m = 9.43 \times 10^2 \frac{(D_{\rm dr}^2 - d_{\rm dr}^2)C^2}{Z^3};$$

$$\sigma_{\rm b}^{\rm b} \le \frac{P_R^{\rm II}}{F_{\rm g}},$$

$$F_{\rm g} = 8ZH - 2Z^2 - 4H^2 \ \text{ for } \ H > \frac{Z}{2};$$

$$F_{\rm g} = 4H^2 \ \text{ for } \ H \le \frac{Z}{2};$$

$$\frac{h_{\rm w}^{\rm r}}{\pi D_{\rm dr}} = r_a \frac{V_{\rm ch}^{\rm r} - V_{\rm r}^{\rm rem}}{F_{\rm bs} V_{\rm fr} H_{\rm dr}},$$

where $V_{\rm ch}^{\rm r}$ is the volume of dispersed material; $n_m$ is the total number of grains on the drill end-face; $R_{\rm dr} = D_{\rm dr}/2$; $n_m^{\rm c}$ is the number of cutting grains; $k_{\rm cg}^{\rm I}$, $k_{\rm cg}^{\rm II}$, $k_{\rm yo}^{\rm I}$, and $k_{\rm yo}^{\rm II}$ are coefficients determining the quantity of cutting grains in the first group (protruding to a height of $0.3H$) and the second group (protruding to a height of $0.09H$); $D_{\rm dr}$ and $d_{\rm dr}$ are the outer and inner diameters of the drill; $C$ is the relative content of diamonds, %; $Z$ is the grain size of diamond powder, µm; $F_{\rm g}$ is the surface of the grain setting in the binder; $H$ is the grain setting depth; $h_{\rm w}^{\rm r}$ is the height of the layer of binder removed per revolution in the abrasive wear model; $r_a$ is the proportionality coefficient; $V_{\rm r}^{\rm rem}$ is the volume of dispersed material removed with lubricant-coolant per revolution of the drill; $F_{\rm bc}$ is the surface area of binder contact with the material under treatment; $V_{\rm fr}$ is the volume of free space between the drill end and the article; $H_{\rm dr}$ is the hardness of the material.

The energy-balance equation describing the diamond-drilling processes can be written in the following form:

$$W_{\rm m} = W_{\rm fr} + W_{\rm d} + W_{\rm a} + W_{\rm em},$$

where $W_{\rm m}$ is mechanical energy supplied to the drilling zone; $W_{\rm fr}$ is the energy spent on friction of the binder against the treated surface; $W_{\rm d}$ is the energy spent on dispersion of the material; $W_{\rm a}$ and $W_{\rm em}$ is the energy of formation of acoustic and electromagnetic waves.

A result of modeling the energy balance of drilling using some data from microcutting modeling (in particular, the stress-variation rate in crack origination) is the description of heat-exchange processes between diamond grains, the binder, and the material being treated and identifying a relationship between the cutting force and the acoustic-emission parameter. This relationship provides a basis for a new generation of adaptive control devices for diamond drilling.

The use of modeling results in specialized software for calculation of efficient cutting regimes for various combinations of initial data has made it possible to improve the efficiency of diamond drilling due to increased output, reduced amount of trimming, and avoidance of breakdown of tools while preserving high quality of treatment.

Modeling results can also be used for the development of new advanced technologies for producing diamond tools able to perform in stressed conditions.

A new tool called MonAliT developed on the basis of the results obtained has unique durability and edge resistance. For instance, a drill 6 mm in diameter provides for treatment of at least 5000 holes in glass 6 mm thick, and up to 8000 holes when satisfying rational operating conditions.

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